

INVESTIGATION ON MISSING FUNDAMENTAL BY A COCHLEA MODEL GENERATING SPONTANEOUS DISCHARGE

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Abstract—It is considered that the pitch(f_0) is produced in auditory centers when we hear a complex tone of $f_1 = n f_0$, and $f_2 = (n+1) f_0$. f_0 is known as missing fundamental. By a cochlea model we try to make clear the mechanism how missing fundamental is generated. The following signal is applied to the cochlea model. $a_1 \sin(2\pi f_1 t) + a_2 \sin(2\pi f_2 t)$. We make an aggregated autocorrelogram of output pulse trains from a cochlea model. We investigate methodically the relation between the information of missing fundamental in the output pulse trains and the values a_i , and n, k in $f_1 = n f_0$, $f_2 = (n+k) f_0$ by the aggregated autocorrelogram.

Keywords – Missing fundamental, spontaneous discharge, cochlea model, aggregated autocorrelogram

1. INTRODUCTION

It is known that most of neurons perform integral pulse frequency modulation (abbreviation IPFM) with refractory period (RP). Refractory period consists of absolute refractory period (ARP) and relative refractory period (RRP). We have investigated the nature of IPFM system with RP and have made clear followings.

Phase - lock phenomenon occurs for an input periodic signal $\{ \sin(2\pi f_1 t) \}$ [1].

The information of f_0 explicitly appears in the aggregated autocorrelogram of pulse trains from the IPFM systems with ARP[2]. (It was made clear experimentally that ARP plays an important role for generating phase-locked pulses)

A pulse train is from the IPFM system with ARP for an input signal $\{ \sin(2\pi f_1 t) \}$.

Another pulse train is from the IPFM system with ARP for an input signal $\{ \sin(2\pi f_2 t) \}$.

where $f_1 = n f_0$, $f_2 = (n+1) f_0$

f_0 is named missing fundamental

It is also known that primary auditory nerves (PAN) in the peripheral auditory system perform IPFM and missing fundamental phenomenon occurs in the auditory system[3]. So, we make a cochlea model and investigate how the information of missing fundamental is contained in pulse trains in the peripheral auditory system.

2. A COCHLEA MODEL

Fig.1 is the block diagram of a cochlea model [2]. The cochlea model consists of a model of Basilar Membrane (BM) and a model of Hair Cell Primary Auditory Nerve(HC PAN). The model of Basilar Membrane transforms an input sound wave into a progressive wave on the Basilar membrane. The model of Hair Cell Primary Auditory Nerve is a neural network which transforms the displacement velocity or the displacement of the Basilar Membrane into pulse trains.

Fig.2 is a model of Basilar Membrane-Hair Cell Primary Auditory Nerve of type I. The part (Hair Cell Primary Auditory Nerve) of this model is a neural network based on physiological observations. An input layer's unit of the neural network is an inner Hair Cell. Each input layer's unit detects the displacement velocity of the Basilar Membrane at each position on the Basilar Membrane. The unit also performs half wave rectification. The output layer's units are Primary Auditory Nerves of type I which perform IPFM with Absolute Refractory Period and generate pulse trains. The name of Neural Network (NN) of 200Hz of type I is applied as follows. The input layer's unit in Neural Network of 200Hz is located at the position of the BM where the envelope peak of the progressive wave of 200Hz appears. Neural Network of 400Hz, Neural Network of 500Hz, etc. are named in the same manner.

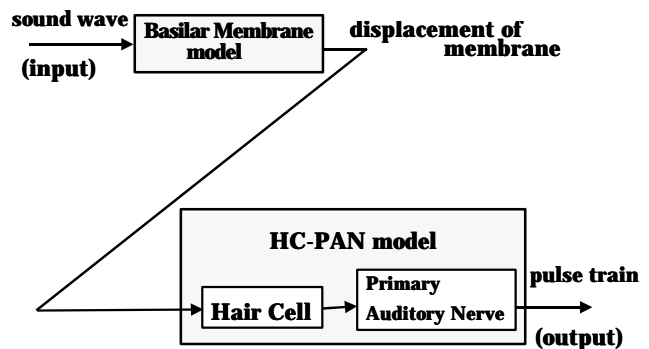


Fig.1. Block diagram of a Cochlea model

IPFM : Integral Pulse Frequency Modulation

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Output layer's units contain the electric power source such as generates spontaneous discharge. For no input signal to an output layer's unit, interval histogram of spontaneous discharge of the unit is of exponential shape. Synaptic weights of NN are fixed. It supposes synaptic weights which are originally fixed or synaptic weights of NN which finished unsupervised learning.

The values of parameters in the cochlea model are followings.

absolute refractory period of primary auditory nerve

1.0 msec

threshold 20.0 mV

frequency of spontaneous discharge 100 events/sec

Fig.3 is the block diagram of a model of Hair Cell – Primary Auditory Nerve of type I (with spontaneous generator).

. METHODS

A following complex tone signal is applied to the cochlea model.

$$\hat{O} a_i \sin (2\delta f_i t + \hat{e}_i)$$

where $\max i = 2$, $\hat{e}_i = 0$, $f_1 = n f_0$, $f_2 = (n+k) f_0$

i.e. a complex tone signal is

$$a_1 \sin (2\delta f_1 t) + a_2 \sin (2\delta f_2 t)$$

We get one group of output pulse trains from NN of f_1 Hz and another group from NN of f_2 Hz(see Fig.4). To see periodicity and structure of pulse trains, we make each autocorreleogram of each group of pulse trains. To see the information of missing fundamental in pulse trains, we make an aggregated autocorreleogram of the autocorreleograms.

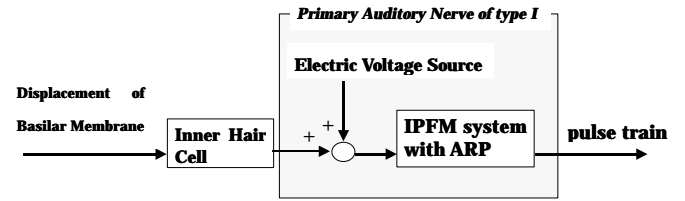


Fig.3. Block diagram of a model of Hair Cell – Primary Auditory Nerve of type I (with spontaneous discharge generator).

IPFM: Integral Pulse Frequency Modulation

ARP: Absolute Refractory Period

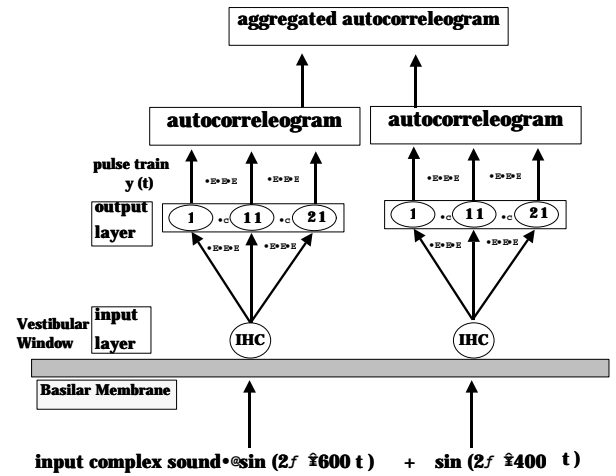
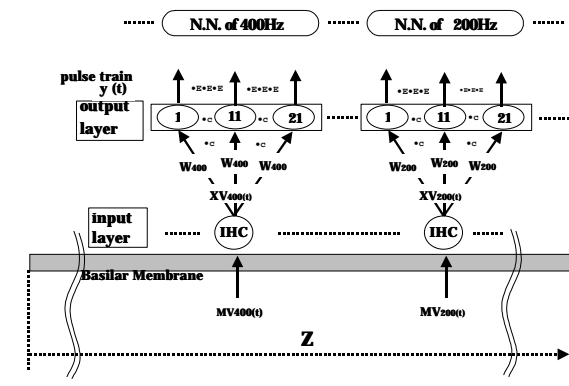


Fig.4. Aggregated autocorreleogram

IHC: Inner Hair Cell



1 11 21 • Primary Auditory Nerves of Type I

IHC • In Inner Hair Cell

W_i • The value of synaptic weight $y(t)$: Pulse train
• The signal proportional to the displacement velocity of the Basilar Membrane

$i=200,400,\text{etc}$

Z • The distance from the Vestibular Window

$\text{net}(t) = W_i \cdot X V_i(t)$ • The input signal to Primary Auditory Nerve

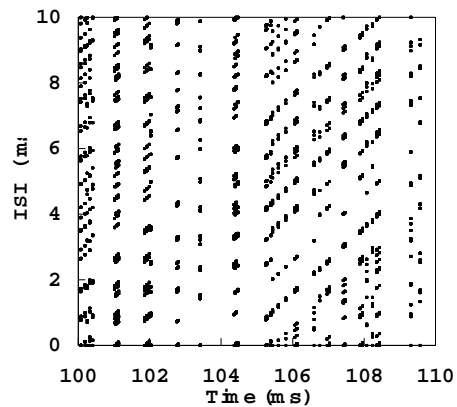


Fig.5. The aggregated autocorreleogram of autocorreleograms

Fig.2. a model of BM-IHC PAN(PAN of Type I)

. RESULTS

Fig.5 is the aggregated autocorreleogram (where $f_1=1200\text{Hz}$, $f_2=1400\text{Hz}$). Fig.6 is the interspike-interval histogram (bin size 0.1msec) of the aggregated autocorreleogram. Peaks of the interspike-interval histogram appear at n times 5 ms ($n=1,2,\dots$) in the interspike-interval histogram (see Fig.6). It means that in pulse trains from NN of f_1 Hz and NN of f_2 Hz there are many pulses whose intervals equal the period (5msec) of missing fundamental f_0 ($f_0=200\text{Hz}$). To extract missing fundamental, we make normalized interspike-interval histogram (Fig.7). Results of extracting missing fundamental are in table 1. Results in changing the value of a_i also are shown there.

Missing fundamental is extracted more clearly in case of $a_1/a_2 = 3/1$ or $1/3$ than in case of $a_1/a_2 = 1/1$.

The smaller k is, the more clearly missing fundamental is extracted. It suggests that the maximum value of k exists.

. CONCLUSION

We made a cochlea model whose primary auditory nerves generate spontaneous discharge too. To see the information of missing fundamental, we have made the aggregated autocorreleogram of the output pulse trains. The relation between the information of missing fundamental and a_i , n , k , in $f_1 = n f_0$, $f_2 = (n+k) f_0$ is investigated systematically.

It is found experimentally that missing fundamental is extracted clearly in case of $a_1/a_2 = 1/1$ (in $a_1 \sin(2\pi f_1 t) + a_2 \sin(2\pi f_2 t)$) and the maximum value of k (in $f_2 = (n+k) f_0$) exists.

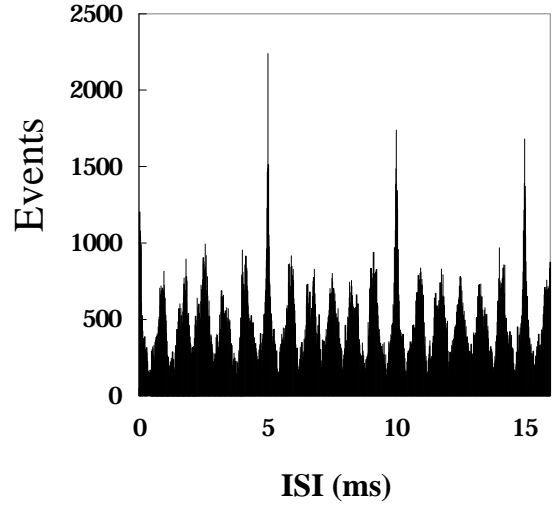


Fig.6. The interspike-interval histogram of the aggregated autocorreleogram (bin size 0.1ms)

an input signal
 $\sin(2\pi 1200t) + \sin(2\pi 1400t)$

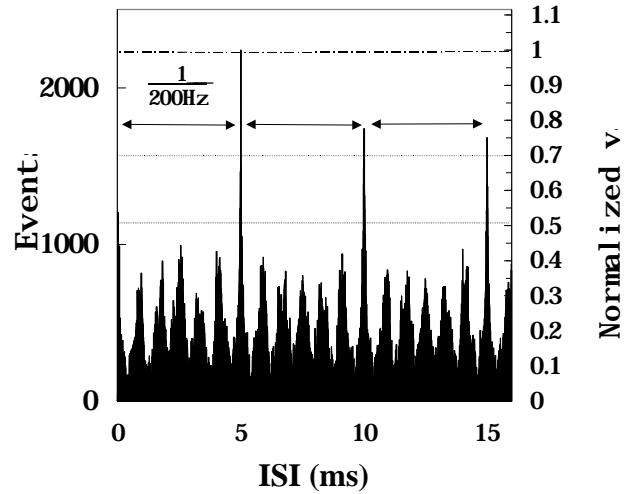


Fig.7. Normalized interspike-interval histogram (thresholds are 0.5 and 0.7)

Table1 Extraction results of missing fundamental

$f_0=200\text{Hz}$

No.	f_1 [Hz]	f_2 [Hz]	n	k	a_1	a_2	extracted missing fundamental[Hz]	
							threshold 0.7	threshold 0.5
1	1200	1400	6	1	1	1	200	nothing
2					3	1	200	200
3					1	3	200	200
4	1200	2200	6	5	1	1	nothing	nothing
5					3	1	nothing	nothing
6					1	3	200	200
7	2000	2200	10	1	1	1	nothing	nothing
8					3	1	200	nothing
9					1	3	200	200
10	2000	2600	10	3	1	1	nothing	nothing
11					3	1	200	nothing
12					1	3	200	200

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